PB85-245975

Assessment of Individual Human Exposures to Ozone in a Health Study

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Prepared for

Environmental Monitoring and Support Lab.
Research Triangle Park, NC

Aug 85

U.S. Department of Commerce
National Technical Information
NTIS

PB85-245975

EPA/600/D-85/195
August 1985

THE ASSESSMENT OF INDIVIDUAL HUMAN EXPOSURES TO OZONE IN A HEALTH STUDY

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CR808536-010

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TECHNICAL REPORT DATA
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1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/D-85/195		PB85 245975/AS

4. TITLE AND SUBTITLE	5. REPORT DATE
The Assessment of Individual Human Exposures to Ozone in a Health Study	August 1985
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Dr. David T. Mage, USEPA Dr. John D. Spengler, HSPH Dr. Mark Raizenne, Environment Canada	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS USEPA ORD/EMSL/MAD RTP, NC 27711	10. PROGRAM ELEMENT NO.
	11. CONTRACT/GRANT NO. CR 8085 36010
12. SPONSORING AGENCY NAME AND ADDRESS USEPA ORD/EMSL/MAD RTP, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE EPA/600/08

15. SUPPLEMENTARY NOTES

C

16. ABSTRACT

The minute dose of ozone delivered to the lower respiratory tract of a subject depends upon the ozone concentration inhaled (X µg/l), the minute volume (Ve l/min) and the fraction(Θ) of the inhaled ozone that penetrates the nasopharyngeal passages to enter the trachea. The ozone concentration (X) depends on the time of day and whether the subject is indoors or outdoors. The minute volume depends on the subject's age, sex, weight, and physical activity level. The fractional deposition of ozone depends on the concentration inhaled (X), the minute volume (Ve), and the mode of breathing (nasal or oronasal). These dependencies are reviewed and a calculation of a daily ozone dosage is presented for a prototypical 12-year old child at summer camp who varies his physical activities in indoor and outdoor settings over a 24-hour period.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
UNLIMITED	UNCLASSIFIED	16
	20. SECURITY CLASS (This page)	22. PRICE
	UNCLASSIFIED	$ 9.95

EPA Form 2220-1 (9-73)

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All opinions expressed are those of the authors. Any policy issues discussed do not necessarily reflect the views of the U.S. EPA or Health and Welfare - Canada.

THE ASSESSMENT OF INDIVIDUAL HUMAN EXPOSURES TO OZONE IN A HEALTH STUDY

Introduction

The computation of an individual dosage of ozone to the respiratory tract of a subject and the objective measure of the health effect can be used to develop a dose response relation for the subject. For the purpose of this paper the total mass of ozone delivered beyond the trachea is taken to be the dosage although not all that ozone reaches the target sites. We assume a relatively constant proportion of the total mass reaches the target sites so the health effect is also relatable to the total mass. We neglect the effect of ozone removed in the nasal tract. This mass of ozone depleted in protective layers and delivered to the target pulmonary air exchange surfaces beyond the trachea in an interval Δt can be calculated by the equation

$$D = \int_{t_1}^{t_1 + \Delta t} X \, Ve \, \Theta \, dt \qquad (1)$$

where D = Dosage, micrograms µg
X = Ozone exposure, µg/liter
Ve = Minute volume, liter/min
t_1 = time at start of integration interval Δt
Θ = fractional penetration beyond the trachea, $0 < \Theta < 1$

This paper discusses these terms in detail and presents a methodology for relating subject's exposure to their dosage, which can be compared to observations of the subject's health. A detailed example of the calculations for a 12-year old boy at a summer camp is presented.

Exposure Assessment

The exposure (X) is the concentration of ozone in the inspired air. Ozone is a secondary pollutant (not emitted into the atmosphere) which is formed in the atmosphere by photochemical reactions, and it usually reaches a maximal value in the afternoon. Because ozone is highly reactive, an indoor microenvironment may provide a protective setting if it contains chemically active surface areas upon which ozone can adsorb and react. A home setting with carpeting, drapes, curtains, and upholstered furniture has large adsorbing surface areas of cotton, wool, and other fabrics which are oxidized and reduce ozone. When air exchange with the outside air is restricted, ozone concentrations are greatly reduced and a subject remaining indoors is protected from high ambient ozone concentration levels.

On the other extreme, a log cabin or other rustic wood structure with wood furniture and minimal fabric content, such as bedding, will provide only a limited amount of protection. In the study described here, a rustic open dining hall at a summer camp was monitored inside using a Columbia Scientific Instrument Company portable ozone analyzer to obtain estimates of the protective effect for ozone exposure to the campers. Figure 1 shows the measured daytime indoor/outdoor ratio (R) as a function of the ambient ozone concentration measured using a Monitor Labs 8410E ozone analyzer 100 meters away from the dining hall. The curve drawn on the figure is the regression equation fit to the hourly average ozone data (Spengler, 1984)[1],

$$R = 0.92 - 0.016/X_a \quad (r2 = 0.82) \qquad (2)$$

where X_a is the ambient ozone concentration, ppm, Xa> 0.017 ppm

For the purposes of this example, we will assume that the same relation applies in the campers' cabins, although their bedding and clothing may reduce the ozone to a greater extent than would be predicted by Equation (2) or Figure 1. Ambient concentrations, X_a, were recorded on an hourly basis throughout the study and are assumed to be uniformly applicable over the area of the camp and lake where the children spent their full 24-hour day.

We, therefore, compute the campers' exposure X in μg/liter during a given hour as

$$X = 1.96(\mu g/liter\text{-}ppm)R\ Xa \qquad (3)$$

where $R = 1$, if subject is outside;
$R = 0.92 - 0.016/X_a$, if subject is inside; and
$R = 0$, if $X_a < 0.017$ ppm

Minute Ventilation

A child's minute volume depends upon many factors such as age, sex, body weight, basal metabolism, and physical activity level. In the camp study we are using for this example, minute volumes of the children were not recorded. However, we have available for each child, their sex, age, height, and weight. In addition, measurements were made of the campers' heart rates in beats/min (BPM) during the various camp activities. Using correlations available from the literature, we developed relations to establish a typical child's activities minute volume during a 24-hour period while the child's activities varied from sleep to heavy exercise.

Colucci (1982)[2] presented an empirical relation for the dependence of children's (mean age 12 years) minute ventilation in liters as a function of heart rate (BPM) as follows:

$$Ve = 1.635 \exp (0.0185\ BPM) \qquad (4)$$

This relation is consistent with other relations in the literature. A basal ventilation of 7.9 m^3/day for an average 12-year old boy is reported by Knelson (1974)[3]. This rate corresponds to 5.5 liter/min which in turn results in a value of 65 BPM using equation 4. A nomogram by Radford, et al., (1954)[4] also predicts a basal tidal volume of 300 ml for a 120 lb child breathing at 18 cycles per minute, which equates to Ve = 5.4 liter/min. Since the sleeping BPM will be lower than the basal BPM, we will assume that the sleeping BPM is 60, which corresponds to a sleeping Ve = 5 liter/min.

Table I shows the average and standard deviations of measured heart rates (BPM), along with the mean ages of the children sampled, as a function of their activity descriptors. Also shown are the minute volumes for the mean heart rates of these activities as predicted by equation 4.

Penetration

When ambient ozone is inhaled through the nose, it is reacted on the moist nasal mucosa surfaces and, consequently, the concentration of ozone penetrating to the trachea will be lower than that inhaled.

Young (1977)[5] reported the penetration (θ) of ozone in the nasal tract as a function of X and Ve for seven male subjects ranging in age from 22 to 48 years, as given in Table II. These results indicate a complicated nonlinear relationship between θ, Ve, and X. This study used unidirectional flow so the normal steady state oscillatory flow conditions may not be accurately modeled.

To our knowledge, the deposition of ozone in the nasopharyngeal tracts of children has not been reported in the literature. Since children have a different pulmonary morphology from that of an adult, the penetration of ozone through a child's nasal tract can vary from the adult penetration by an unknown factor. For the purpose of the example calculations, we will assume that for a given ambient X_a the penetration of ozone into the child's respiratory tract below the pharynx is the same as for these seven adults at the same measured ventilation rate.

Smoothed French curves through these penetration factors are plotted on Figure 2. If we assume a zero order rate of reaction at very low concentrations so that fractional penetration (θ) goes to zero in the limit as inhaled ozone concentration goes to zero, then it may be possible to draw the horizontal line of 0.00 penetration for any value of Ve and interpolate between 0 and 0.10 for any intermediate concentration $0 < X < 0.10$ ppm. An empirical exponential relation using θ at 0.5 ppm as an upper asymptote will be assumed for each value of Ve as follows:

$$\theta_X = \theta_{.5} \, (1 - \exp[-kX]) \tag{5}$$

The variable value of k can be computed from knowledge of $\theta_{.1}$ at X = 0.10 ppm by

$$k = -10 \ln([\theta_{.5} - \theta_{.1}]/\theta_{.5}) \tag{6}$$

Since all Xa data are < 0.11 ppm the error in choice of the upper asymptote at 0.5 ppm should have minimal effect.

Procedure for Dosage Computation

At the summer camp under study, the day was broken up into 13 periods of activity, during which we assume that the child's activity is constant. In the first four columns of Table III are shown the period number, activity description, time period, and total minutes of activity. We, therefore, perform the integration of equation (1) by a summation of $(X \; Ve \; \theta \; \Delta t)_i$ over the 13 periods as follows:

$$\text{Dose} = \sum_{i=1}^{13} (X \; Ve \; \theta_X \; \Delta t)_i \tag{7}$$

where $X = 1.96 \; R \; X_a$, µg ozone/liter (3)

$Ve = 1.635 \exp(0.0185 \; BPM)$ (4)

$\theta_X = \theta_{.5} \, (1-\exp[10 \ln([\theta_{.5} - \theta_{.1}]/\theta_{.5})RXa])$ (8)

where θ_X, $\theta_{.5}$ and $\theta_{.1}$ are evaluated at Ve.

For an example calculation, let us look at period 6, 12:00 - 2:00 during which time the children had lunch in the dining hall and rested in the

cabins. We estimate the heart rate during lunch and rest as 81 BPM which predicts Ve = 7.3 liter/min using equation (4). Between 12:00 and 1:00 the ambient ozone (X_a) was 0.071 ppm and between 1:00 and 2:00 the value of X_a was 0.086 ppm, giving an average value of X_a = 0.078 ppm. Using equation (2) we predict an average indoor/outdoor ratio R = 0.71, so the average exposure (X) in period 6 is (0.071)(0.078 ppm) = 0.055 ppm (the measured hourly values of X in the dining hall in the 2-hr period were 0.056 and 0.059 ppm).

To estimate the penetration (Θ) of ozone at X = 0.055 ppm and Ve = 7.3 liter/min, we use Figure 2 to estimate for Ve = 7.3 liter/min that $\Theta.5$ = 0.28 @ X = 0.50 ppm and $\Theta.1$ = 0.22 @ X = 0.10 ppm. Using equation (8), we obtain for X = 0.055 ppm,

$$\Theta(0.055 \text{ ppm}, 7.3 \text{ lpm}) = 0.28(1-\exp[10 \ln([0.28 - 0.22]/0.28)0.055]) = 0.16$$

The dosage (D_i) during the 6th period is then computed as

$$D_6 = (0.108 \text{ µg/liter})(7.3 \text{ liter/min})(0.16)(120 \text{ min}) = 15.1 \text{ µg of ozone}$$

Summing over the 13 periods, we obtain a total dosage of 250 µg past the nasopharynx for the 12-year old camper breathing through his nose. It should be noted that oronasal breathing will increase the dosage since ozone in the portion of the air bypassing the nasal tract will not be so completely removed by the oropharynx.

Intersubject Variation

For each activity listed in Table I, a variation in heart rate was observed as shown by the standard deviation (S.D.). To show the possible effect of physiological variation between subjects, we repeated the computations of Table III for the 12-year old child who has a one-standard deviation (+1 σ) higher heart rate for each activity. The concentration (X) and intervals (Δt) will be identical to those in Table III, but the ventilation rates will increase and, consequently, the penetration will also be increased. For this computation we assume a S.D. of 10 BPM for sleep, so a heart rate of 70 will be assumed in the calculation. Table IV shows the computation of the dosage for the +1σ camper performing the same activities as the average camper in Table III.

The one-day ventilation of the + 1σ camper is 14.9 m^3, which is 33% higher than the average camper's one-day total of 11.2 m^3. However, because the penetration increases with increasing ventilation rate, the total dose increased 71% from 250 µg to 427 µg.

Discussion

These computations for the dosage of ozone to the lower respiratory tract indicate that measurement of an ambient exposure is not sufficient to characterize the potential effect on a subject who can be indoors and outdoors with varying activity throughout the day.

Although the results presented here are quantitative they should be treated as qualitative due to our use of several approximations and untested assumptions that were necessary in order to allow computations to be made. These assumptions are as follows:

1) A constant proportion of ozone entering the lower respiratory tract reaches the target sites.

2) The fractional penetration (θ) of ozone goes to zero in the limit as X goes to zero and θ goes to 0.5 in the limit as X becomes >>0.

3) Nasal tract penetration of ozone for children is similar to the measured penetration (θ) for adults.

4) The children's minute volumes (Ve) increase exponentially with heart rate (bpm). Other characteristics not measured in this study, such as physical training and condition may influence Ve.

5) The child's activity rate remains constant over the activity period. This is questionable since only trained swimmers can swim 45-minutes at > 123 bpm.

6) The children are only nose breathing.

7) The indoor/outdoor relation is site specific and may not be applicable in cabins or other microenvironments.

The nonlinear interaction of penetration with concentration and ventilation rate requires that a detailed activity log be kept so that the subject's location (indoor vs outdoors) and physical activities can be related to the measured ozone. The calculation of intersubject variations indicate that a one-standard deviation change in heart rate may correspond to a 70% variation in computed dosage for the assumptions and conditions described in this paper. It is, therefore, suggested that in future studies that the subject's ventilation be measured as a function of heart rate under controlled conditions at the start of the study so that a pulse entry in the activity log can be used to help evaluate the varying ventilation rate during the study period. Individual differences in the threshold level at which the subject begins to mouth breathe may also influence results of cohort studies, and some indication of whether the subject is a mouth breather or not may be useful for interpretation of the study results.

Simulations have shown that computation of dosage-response may improve on results from an exposure-response (6). It is suggested that a methodology, such as presented here, that can ascribe an individual estimate of dosage to each subject may be a useful tool for improving classifications of subjects into low-medium-high exposure groups.

TABLE I

Activity Assessment: Heart rates and computed minute volumes (1/min).

Method: Beginning day 01 through to day 09, research assistants attended various activity sessions. Using a "Pulse Bar" device, they randomly asked campers (whether in the study or not) to hold the bar with both hands, extended arms about pelvis height. A digital display of the heart rate was recorded and the camper's age and sex was recorded.

Activity	# of Records	Mean Age	Mean Heart Rate	S.D.	Ve
Archery	61	12.7	105	17.3	11.4
Arts and Crafts	84	12.1	90	14.7	8.6
Canoeing*	79	12.2	105	18.6	11.4
Hebertism***	97	12.8	124	25.3	16.0
Sailing*	12	13.8	95	13.7	9.3
Softball	60	12.3	119	21.5	14.8
Sports and Games	57	11.9	124	21.4	16.0
Swimming*	58	12.7	123	18.0	15.8
WOW (experimental play)	72	10.7	98	18.3	10.0
Rest**	32	11.2	81	14.2	7.3

* Rates were taken at the dock, therefore the heart rates represent post-activity or recovery values.

** Note this sample was from the actual group that had volunteered to perform the study after having performed the lung tests on one occasion. It differs from the activity sample randomly measured from all children attending the camp.

***Obstacle course with tree climb, rope swing, etc.

TABLE II

Mean Penetration of Ozone Past the Nasal Tract of 7 Adult Males

Ve	Fractional Penetration (θ)[5] 0.10 ppm O_3	0.50 ppm O_3
1	0.015	0.016
2	0.021	0.050
5	0.120	0.177
15	0.354	0.416
30	0.454	0.548
50	0.536	0.595

TABLE III

Period(i)	Activity	Time Hours	Δt Minutes	BPM	Ve Lit/min	X_a ppm	R	X ppm	Θ	$D_i=(1.96 \times V\Theta\Delta t)_i$ Micrograms
1	Sleep	0- 7:30	450	60	5.0	0.026	0.32	.008	0.015	0.5
2	Wake up Breakfast/Clean Up	7:30- 9:30	120	81	7.3	0.036	0.48	.017	0.065	1.9
3	W.O.W. (Experimental Play Period)	9:30-10:20	50	98	10.0	0.039	1	.039	0.17	6.5
4	Swim	10:20-11:10	50	123	15.8	0.040	1	.040	0.23	14.2
5	Sports	11:10-12:00	50	124	16.0	0.054	1	.054	0.28	23.7
6	Lunch Rest	12:00- 2:00	120	81	7.3	0.078	0.71	.055	0.16	15.1
7	Canoeing	2:00- 2:50	50	105	11.4	0.098	1	.098	0.31	33.9
8	Hebertism	2:50- 3:40	50	124	16.0	0.105	1	.105	0.37	60.9
9	Arts & Crafts	3:40- 4:30	50	90	8.6	0.110	1	.110	0.26	24.1
10	Free Time	4:30- 5:20	50	90	8.6	0.100	1	.100	0.25	21.1
11	Dinner	5:20- 7:00	100	81	7.3	0.095	0.75	.071	0.19	19.3
12	Evening Program	7:00-10:00	180	90	8.6	0.071	0.69	.050	0.17	25.8
13	Sleep	10:00-24:00	120	60	5.0	0.060	0.66	.040	0.06	2.8
TOTAL		24 hr	1440		11.2 m^3					250 µg

TABLE IV

Dosage Calculation for a +1σ Camper

Period	Δt Minutes	X ppm	BPM	V_e	Θ	$D_j = 1.96 \times V_e \Theta \Delta t$(μg)
1	450	0.008	70	6.0	0.021	0.9
2	120	0.017	95	9.5	0.084	3.2
3	50	0.039	116	14.0	0.21	11.2
4	50	0.040	141	22.2	0.25	21.8
5	50	0.054	145	23.9	0.31	39.2
6	120	0.055	95	9.5	0.202	24.8
7	50	0.098	124	16.2	0.36	56.0
8	50	0.105	149	25.7	0.44	116.4
9	50	0.110	105	11.4	0.32	39.3
10	50	0.100	105	11.4	0.31	34.6
11	100	0.071	95	9.5	0.233	30.9
12	180	0.050	105	11.4	0.11	44.3
13	120	0.040	70	6.0	0.087	4.9
Total	24 hr			14.9 m^3		427 μg

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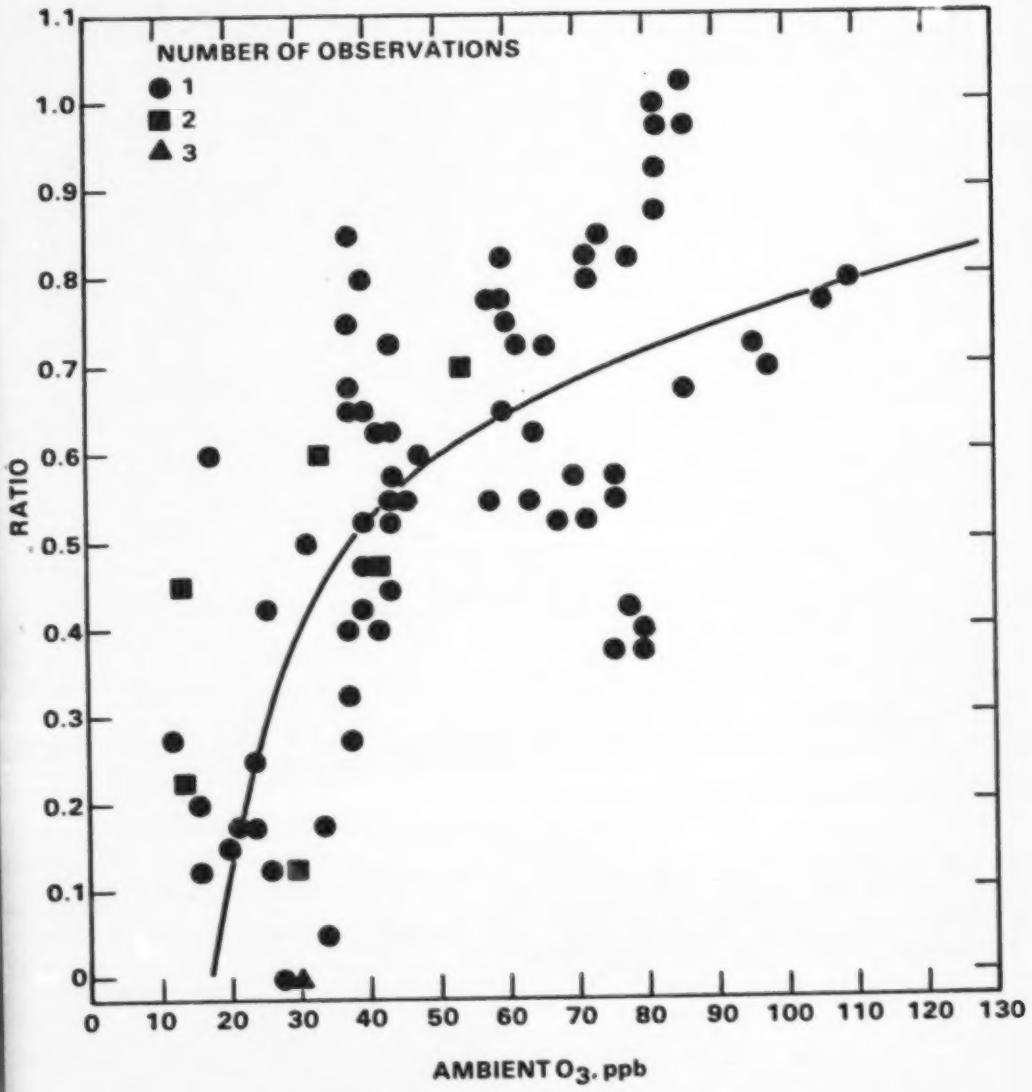
Figure Titles

Figure 1 - Measured ratios of indoor ozone to ambient ozone as a function of ambient ozone concentration

Figure 2 - Fractional penetration of ozone beyond the trachea of 7 adult males as a function of minute volume during nasal breathing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0.8
0.7
0.6
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0.4
0.3
0.2
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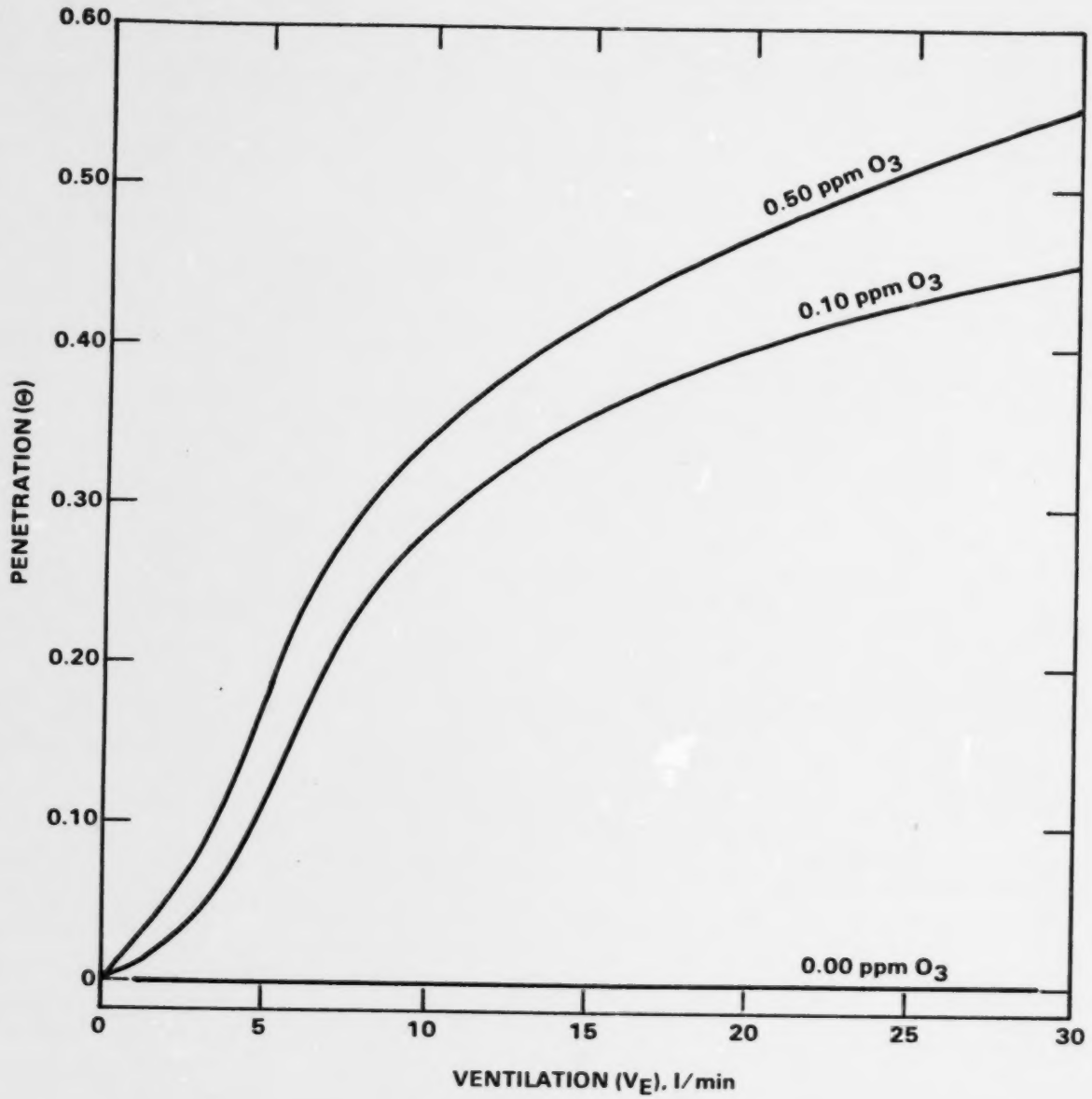
AMBIENT O_3, ppb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0.50
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0.30
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PENETRATION (θ)
0.50 ppm O3
0.10 ppm O3
0.00 ppm O3
0
5
10
15
20
25
30
VENTILATION (VE), l/min